Balkanized research in ecological engineering revealed by a bibliometric analysis of earthworms and ecosystem services.

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Abstract

Energy crisis, climate changes and biodiversity losses have reinforced the drive for more ecologically-based approaches for environmental management. Such approaches are characterized by the use of organisms rather than energy-consuming technologies. Although earthworms are believed to be potentially useful organisms for managing ecosystem services, there is actually no quantification of such a trend in literature. This bibliometric analysis aimed to measure the evolution of the association of ‘earthworms’ and other terms such as ecosystem services (primary production, nutrient cycling, carbon sequestration, soil structure and pollution remediation), ‘ecological engineering’ or ‘biodiversity’, to assess their convergence or divergence through time. In this aim, we calculated the similarity index, an indicator of the paradigmatic proximity defined in applied epistemology, for each year between 1900 and 2009. We documented the scientific fields and the geographical origins of the studies, as well as the land uses, and compare these characteristics with a 25 year old review on earthworm management. The association of earthworm related keywords with ecosystem services related keywords was increasing with time, reflecting the growing interest in earthworm use in biodiversity and ecosystem services management. Conversely, no significant increase in the association between earthworms and disciplines such as ecological engineering or restoration ecology was observed. This demonstrated that general ecologically-based approaches have yet to emerge and that there is little exchange of knowledge, methods or concepts among balkanized application realms. Nevertheless, there is a strong need for crossing the frontiers between fields of application and for developing an umbrella discipline to provide a framework for the use of organisms to manage ecosystem services.

Keywords: bibliometric analysis; biodiversity; earthworms; ecological engineering; ecosystem services; similarity index.

INTRODUCTION

Food and livelihood crisis, floods, landslides, climate change, biofuel, human population growth, desertification, urban sprawl, pollutions…: all these threats are well known by the public and policy makers, but few excepted soil scientists are aware that soils are at the heart of these problems and that, therefore, soil management may help solve many of them. The ecosystem services concept (Costanza et al. 1997; Daily 1997) could help bridge the gap between science and policy, by translating what ecologists call ecosystem functions and processes (e.g. primary production, soil structure maintenance, carbon sequestration…) into benefits for society (e.g. food, fuel and fiber production, fertility, climate regulation…), which are of more interest to policy makers. Soils have been recognized for delivering major ecosystem services such as support services (nutrient cycling), provisioning (production for food, wood, fibre…), regulating services (flood regulation, climate regulation, pest control…) and cultural services (burial of the dead, preservation of archeological remains…) (Millennium Ecosystem Assessment 2005; Dominati et al. 2010). Soil biodiversity is largely responsible for many of these services (Barrios 2007; Brussaard et al. 2007), and soil invertebrates are known to be major actors (Lavelle et al. 2006). Earthworm biomass is the largest of all animal biomass in terrestrial ecosystems that are not subjected to long periods of drought or freezing (Lavelle and Spain 2001). They can be considered as keystone species (Power and Mills 1995), especially due to their action as ecosystem engineers (Jones et al. 1994), i.e. organisms with the capacity to create, modify and maintain habitats for other species through physical modification of their environment; as such, earthworms are particularly relevant for the restoration of ecosystems (Byers et al. 2006). Earthworms affect many ecosystem services (Blouin et al. 2013). When they ingest soil, they modify the pore size distribution by creating macropores (their galleries) or microporosity within their casts, which, in turn, regulates the distribution of water and air (Bastardie et al. 2005). By digesting some of the organic matter ingested, or by making it available to microorganisms, earthworms participate in nutrient cycling (Lavelle et al. 2004). They have a beneficial effect on plant growth and increase primary production (Scheu 2003). Earthworms can also stimulate the degradation of organic pollutants or the solubilization of heavy metals (Sizmur and Hodson 2009), which can then be removed by phytoextraction. Due to their active role in the formation of humus, they contribute to the stabilization of soil organic matter and to carbon sequestration. Earthworms are therefore potentially useful for the management of biodiversity and ecosystem services.

However, academic knowledge about the impact of earthworms on biodiversity and ecosystem services is maybe balkanized into different disciplines: for example, soil structure can be studied by soil physicists, nutrient cycling by soil chemists, primary production by plant scientists… This specialisation could prevent the emergence of an integrated framework for dealing with the fact that one single species impacts simultaneously several ecosystem functions and services. To overcome problems relative to multifunctionality, the development of an ecological discipline for environmental management is required. One particularly promising approach is ecological engineering, which consists in having the job done by organisms. More precisely, it consists in harnessing the inherent energy and activity of living systems to replace the technology and external sources of energy used in traditional engineering approaches (Odum 1962). Although this idea is seductive, ecological engineering would reach its objective only if three major challenges are overcome: the ethical, the relational, and the intellectual (Jones 2012).

The objectives of this study were to assess, through a bibliometric survey, the state of development of these research areas and to better identify promising research and management directions. Specifically, we sought to answer two questions that might provide us with an overview of the development of this research field: (a) Are biodiversity and ecosystem services less, equally or more used in research on earthworms, with regards to their use in scientific literature in general? (b) Is their an operational approach or discipline, such as ecological engineering, emerging for the use of earthworms in ecosystem management? To answer these questions, we need a specific method to investigate the available database resources. Bibliometric analyses, developed in applied epistemology, aimed at following the evolution of concepts or concept associations through time, especially to study the increasing or decreasing relevance of these concepts to scientists through their use (Chavalarias and Cointet 2009). The bibliometric approach is quantitative and taken in order to determine (i) if research associating earthworms and ecosystem services or ecological engineering has increase over the last decades, (ii) where the research had been conducted, (iii) which academic fields have contributed to it and (iv) which land use types were studied. However, the bibliometric analysis was not carried out to provide insights into the rationale or qualitative aspects of the links established by authors between earthworms and ecosystem services or ecological engineering. This aspect has been dealt with recently in a detailed literature review (Blouin et al. 2013).

MATERIALS AND METHODS

The setting up of the glossary

This work aimed at assessing, by means of a bibliometric analysis, the available ecological knowledge for the implementation of proactive strategies recommended by the MEA. The bibliometric analysis was based on keywords because they constitute an adequate description of the contents of the referenced articles (Ying et al. 2001). In order to choose and structure the keyword lists we took a three-step approach. First of all, a list of ecosystem services impacted by earthworms was drawn up by international scientific experts from all continents in a workshop held in Grenoble (France) in 2009 (see Acknowledgements). Secondly, a parallel qualitative review about 200 scientific references (Blouin et al. 2013) helped in identifying keywords about ecosystem functions and processes related with these ecosystem services. The third step was to carry out searches on the Web of Science to test the relevance of the selected keywords and to identify additional keywords. The lists of keywords were modified to include the newly identified ones and to eliminate those deemed poorly relevant. During this step, we noted that removing or adding one keyword from our lists had few consequences on the number of matches, probably due to a certain redundancy among keywords of a given theme. The final keyword lists are given in Table 1.

The sets of keywords were used to query the following Web of Science references databases from 1900 to 2009: Science Citation Index Expanded (SCI-EXPANDED)--1899-present ; Conference Proceedings Citation Index- Science (CPCI-S)--2000-present ; Index Chemicus (IC)--1993-present) and social databases (Social Sciences Citation Index (SSCI)--1956-present ; Arts &

Humanities Citation Index (A&HCI)--1975-present ; Conference Proceedings Citation Index-Social Science & Humanities (CPCI-SSH)--2000-present).

Paradigmatic proximity

Our row data was the number of matches with searches for the themes or the associations of themes described in Table 1. For example, the association between Earthworm* and Primary Production* (i.e. a search combining the two lists of keywords "earthworms OR annelid OR oligocheta OR vermicompost" AND "Primary production OR plant growth OR plant production OR grain yield OR plant biomass OR aboveground biomass OR belowground biomass OR seed dormancy OR seed germination") targeted the scientific literature that linked earthworms to primary production. To track the convergence or divergence of these themes in the literature, we used the similarity index, a good indicator of paradigmatic proximity (Callon et al. 1991; Chavalarias and Cointet 2008). The similarity index is a measure of themes co-occurrence. To assess it, queries were designed to count the number of publications that could be assigned to each theme. Given n_i the number of publications referring to the theme i (e.g. Earthworms*), n_j the number of publications referring to the theme j (e.g. Primary Production*) and $(n_i \cap n_j)$ the number of publications associating term i and term j during a time t, the similarity index is equal to the probability that an article contains the term association $(n_i \cap n_j)$ in a database containing N references, divided by the probability that the database contains either i or j. The similarity index indicating the paradigmatic proximity between n_i and n_j is calculated as $(n_i \cap n_j)/(n_i * n_j)$ (Chavalarias and Cointet 2008). We calculated this index in each year to follow the co-occurrence of the theme Earthworm* and each of the others themes. This provided us with a dynamic picture of each of the associations and allowed us to determine if there was a significant convergence or divergence between them.

Features of theme associations

The country of origin of the research was recorded to gain some insights in the socio-economic context of the research on earthworms and ecosystem services (who is interested in this research?). Papers were attributed to countries based on the institutional affiliations as given in Web of Science. A paper was attributed to a country if the paper contained at least one address from that country/territory. All addresses were taken into account, not only the address listed first. A given paper was therefore attributed to several countries.

Research about earthworms and ecosystem services is likely to be interdisciplinary. To confirm this assumption and to depict the range of scientific fields involved in this research, we used the 'subject categories' in Web of Science. These have been established over time by the editors responsible for the various subject areas of the database. Each paper was associated with one single subject category, corresponding to the subject category of the journal in which it had been published. Assignation of a journal to a category is continuously updated, by looking at the journals in which papers from the journal of interest have been cited; this makes difficult the reproduction of our study for this aspect.

The kind of land use is also an important feature of the research on earthworms and ecosystem services. It provides information on the business sectors (agriculture, forestry, pollution remediation…) concerned with our research subject. We therefore looked for land use (forest, pasture, arable soil…) in the abstract of bibliographic references.

By comparing geographical origin of the papers as well as the kind of land use studied with those found in a previous review about “earthworm biostimulation” (Brun et al. 1987), we hoped to obtain some insight into the temporal trends of these subjects.

RESULTS

Data corpus

There are undoubtedly irrelevant references among results. However, due to the very large variety of authors' viewpoints on the link between earthworms and ecosystem services, our sorting between "relevant" and "irrelevant" publications would inevitably be subjective. Because our main question was a comparison between the evolution of the association earthworm-ecosystem services and earthworm-ecological engineering, we privileged an objective and repeatable survey, in which the proportion of irrelevant references was assumed to be approximately the same for each theme and for different years.

We found about 6000 papers results for Earthworm*, 130000 for Ecological Engineering* more than 2 million for all services taken together, and more than 600 000 for Diversity*, corresponding to a total of almost 3 millions papers (Table 2). The number of results for ecosystem services crossed with the Earthworm* theme decreased in the following order: Nutrient Cycling* > Diversity* > Soil Structure* > Pollution Remediation* > Primary Production* > Carbon Sequestration*. Only 178 publications were identified when the themes Earthworm* and Ecological Engineering* were crossed.

The evolution of theme association

We investigated the evolution of associations between Earthworm* and the other themes (Ecological Engineering*, Diversity* or one ecosystem service). In this 110 years bibliometric analysis, keyword co-occurrence is a recent event. The first ecosystem services to be associated with Earthworm* were Nutrient Cycling* in the late 1960's, Pollution Remediation* in the early

1970's, then Diversity* and Soil Structure* in the late 1970's, and finally Primary Production*, Carbon Sequestration* and Ecological Engineering* in 1990. Linear regression was used to model the relationship between the yearly similarity index values $(n_i \cap n_j)/(ni * nj)$ and the year of publication (Fig.1). We observed a significant increase of term association, as described by the similarity index, between Earthworm* and each service (p-value of the slope always < 0.03 and often < 0.001). The slope of the association between Earthworm* and each services according to time was found to decrease in the following order: Primary Production* > Diversity* > Pollution Remediation* > Nutrient Cycling* > Soil Structure* > Carbon Sequestration*. The r^2 correlation coefficient was decreasing in a similar order: Nutrient Cycling* > Primary Production* > Diversity* > Pollution Remediation* > Soil Structure* > Carbon Sequestration*. In contrast, there was no significant increase in the paradigmatic proximity between Earthworm* and Ecological Engineering* (p-value = 0.16) (Fig. 1), illustrating the fact that both these themes are not converging.

Origin of studies

In Figure 2 are represented the geographical origins of the 4864 articles citing simultaneously Earthworm* and another theme, identified in the Table 2. Three countries contributed a high percentage of papers to all the investigated services: USA, France, and Germany (respectively about 25, 15 and 15% on average). England was also an important contributor, except for the theme Carbon Sequestration*. In addition to these four main contributors, Carbon Sequestration* was studied in Brasil, Spain, Italy and Switzerland; Pollution Remediation* was studied in the Netherlands and India; Diversity* was studied in Australia; Nutrient Cycling* was studied in India, the Netherlands, Spain and Canada; Primary Production* was studied in India, Australia, Brasil; Soil Structure* was studied in Australia, Netherlands and Canada. When analyzed by continents rather than by countries (data not shown), we found no contribution >4% for Africa, whatever the ecosystem service. Whereas all ecosystem services included in this study were studied in some (sub) continents, such as Europe and North America, areas of expertise on specific services have been developed in other continents. For instance, Asia is mainly represented for Primary Production*, Nutrient Cycling* and Pollution Remediation*. Oceania is mainly involved in research on Diversity*, Soil Structure* and Primary Production*. South America is mainly interested in Carbon Sequestration*. Regarding studies associating Earthworm* and Ecological Engineering* (n = 178), England, France, USA and India were the most active countries, gathering more than 50% of these studies (Fig. 2). About 25% of remaining studies were conducted in Europe. Brasil and Australia were also significantly represented.

Scientific fields

We compared subject areas of papers associating Earthworm* and another theme to measure the multidisciplinarity of this research (Fig. 3). The main 'subject area' given by the Web of Science was soil science, but ecology and environmental sciences were also well represented. Some differences in proportions were observed: Nutrient Cycling* was particularly discussed in soil science. Soil Structure* was well represented in soil sciences and agronomy sciences. Carbon Sequestration* was studied in soil sciences, as well as in plant sciences. Pollution Remediation* was particularly represented in environmental sciences, environmental engineering and toxicology. Diversity* was particularly discussed in ecology and zoology. Primary Production* was found in agronomy, agriculture and plant sciences. Ecological Engineering* was represented in soil science, ecology, environmental sciences, agriculture as well as biotechnology and applied microbiology.

Land use

Among studies on both Earthworm* and Ecological Engineering* (n = 178), forests were the main documented land use (41%), followed by grasslands (26%) > arable soils (16%) > excavated soils (9%) > wetlands (4%) > deserts (4%).

DISCUSSION

Methodological remarks

The bibliometric analysis is not a panacea for understanding the evolution of science. Despite the advantages linked to repeatability, quantification and statistical modelling, it does not encompass qualitative aspects relative to the cognitive links established by researchers between earthworms and ecosystem services, diversity or ecological engineering. Only by reading the papers to check the relevance of term associations, more precision in the results and more depth in the interpretation can be obtained. This however requires a subjective choice of 'relevant' and 'non relevant' papers, without a quantitative description of criteria taken for this categorization, which prevents the same analysis to be reproduced. We think that classical literature reviews (Barrios 2007; Blouin et al. 2013; Brussaard 2012; Brussaard et al. 2007; Dominati et al. 2010; Lavelle et al. 2006) are more adapted for this kind of argument.

Another problem with literature reviews, either classical or bibliometric, is the list of keywords taken into account in the search for references. Keywords are clearly subjectively chosen. We think that keyword lists have to be submitted to a sufficient number of experts in the scientific fields to make them the most exhaustive. Final keyword lists should always be presented in the paper for transparency.

Features of the research field as compared with a previous study

Evolution of geographical origin

There are probably some bias in the comparison between our results and those of the review on "biostimulation" by earthworms (Brun et al. 1987) (n = 59), as this previous review referred also to grey literature, with papers in the French language. We found that some countries already active 24 years ago contribute still significantly to the field (France, England, USA and Netherlands). Differences were also observed: USSR/Russia and New Zealand which were major contributors in the 1987 review disappeared in the group of countries with less than 4% of the publications in 2009. Some countries from the South have emerged as major contributors, especially India and Brazil. This highlights the relative increasing investment of these large modern countries in research, or their growing interest for ecological approaches to environmental management: India is indeed a major contributor in vermiconpost science, and Brasil as a strong research effort in agroecology. Other smaller, developing countries which share common features with India or Brazil are likely to be interested in the management of earthworms for soil ecosystem services; their growing size and increasing research effort will probably make them significant contributors in the next decades.

Evolution of land-use studied

Results relating to land use also diverged from the cases studied by Brun et al. (1987), who found that the frequency at which the different land uses were referred to in the literature was as follows: arable soil (29%) > grassland (25%) > excavated soil (24%) > wetland (13%) > forest (9%). The discrepancy between their study and what was found here indicates that there has been an increase in interest in ecosystems that are less affected by human activity (forest and grasslands). This can be explained by a growing interest in more "natural" ecosystems that has resulted from an awareness that these ecosystems provide multiple ecosystem services.

Evolution of theme associations

Appearance of themes co-occurrence

The bibliographic survey of the last 110 years showed that co-occurrence of Earthworm* and the different ecosystem services is a recent event which began less than 50 years ago. The first emerging ecosystem services associated with Earthworm* were Nutrient Cycling*, together with increasing concerns over biogeochemical cycles. The co-occurrence of Diversity*, Pollution Remediation* and Soil Structure* and Earthworm* was related to the awareness of the loss of biodiversity and soil degradation and erosion (industries, dust balls…). Surprisingly, the co-occurrence of Primary Production* and Earthworm* appeared relatively late, probably because of the long reciprocal ignorance of plant and animal ecology, and to the agrochemical paradigm in agriculture, which neglected biological regulation in agrosystems. However, the convergence between these two themes was the strongest observed in this study (Fig. 1). The co-occurrence of Carbon Sequestration* with Earthworms* appeared in 1990 with the awareness of climate change. The co-occurrence between Ecological Engineering* and Earthworm* appeared later in the same decade, indicating the recent interest in earthworms in environmental management.

The quantitative appraisal of the dynamic co-occurrence of the theme Earthworm* with the themes relating to ecosystem services, Biodiversity* or Ecological Engineering* suffers several interpretations, which are not equivalent in terms of consequences for science and management efforts.

Earthworms and ecosystem services

Our results showed an increased in the paradigmatic proximity between Earthworm* and each of the ecosystem services. The scientific community appropriated the ecosystem services concept quickly and the number of studies focussing on ecosystem services has increased rapidly during the last decades (Vihervaara et al. 2010). The different ecosystem services (primary production, carbon sequestration, nutrient cycling…) have gained an increasing use, and one can wonder if they just became buzzwords that help to have a paper published. This is certainly not the case since the similarity index, noted $(n_i \cap n_j)/(n_i * n_j)$, is an indicator which reports the evolution of the association between two themes i and j to the individual and independent evolution of i and j (Chavalarias and Cointet 2008). As a consequence, the growing use of ecosystem services can not explain the growing association of Earthworm* and ecosystem services.

The observed increase in association between earthworms and ecosystem services is encouraging and calls for intensification in several directions. One way of making progress in the use of earthworms as a tool for the management of ecosystem services would be to use new techniques and methodologies to improve our basic knowledge about earthworm ecology. Molecular taxonomic studies continue to reveal that what were considered species are in fact assemblages of several taxa (Iglesias Briones et al. 2009; Dupont et al. 2011), or that supra-family taxa are para or poly-phyletic (James and Davidson 2012). Genetic markers also provide relevant tools to follow large scale movements, and evaluate passive dispersal, i.e. through human activities, in the aim to understand species invasions (Hale 2008). Earthworm tagging with Visual Implant Elastomer (VIE) (Northwest Marine Technology Accessed October 2012) is a promising technique for following the movements of earthworms (Butt et al. 2009) at small scale to understand active dispersal and optimize inoculation methods (Mathieu et al. 2010). Moreover, soils are opaque environments which prevent direct observations of earthworm behavior and the resulting effect on soil structure. New methods such as X-ray tomography are being used increasingly to understand earthworm burrows and water movement (Joschko et al. 1991; Jegou et al. 1999; Jegou et al. 2001; Capowiez et al. 1998; Bastardie et al. 2003b). Radio-labelling of earthworms can be use to determine their small scale movement in soil, *in situ* (Capowiez et al. 2001; Bastardie et al. 2003a).

More ‘functional’ studies focussing on the effect of earthworms on specific ecosystem services are also needed. Soil formation, a very long term process, is poorly documented; research conducted by Darwin in his backyard is still considered as a rare and isolated work in this area (Darwin 1881; Feller et al. 2003). Models indicate that long term research is also essential to determine whether the positive effects of earthworms on primary production through nutrient cycling can persist without changes in nutrient inputs in or outputs from the system (Barot et al. 2007). For some services, there is a need for synthetic studies summarising the huge quantities of data that are available, through literature reviews and meta-analyses. The contributions of Brown et al. (1999) or Scheu (2003) have accomplished this for earthworm impact on primary production. More recently, the review of Sizmur and Hodson (2009) on the removal of heavy metals by earthworms and the meta-analysis by Lubbers et al. (2013) on greenhouse gas emissions by earthworms are significant contributions to understand the potential of earthworms for respectively pollution remediation and climate regulation. To our knowledge, there are no such quantitative contributions for nutrient cycling, soil structure or cultural services. We also need more robust data from earthworm studies regarding soil characteristics, vegetation types, climate data, earthworm identification to species level and the presence of other soil microfauna recorded as routine, with the aim to assess the context-dependency of earthworm effects in these meta-analyses.

Earthworms and biodiversity

We observed a significant increase in the association between Earthworm* and Diversity*, suggesting that the links between earthworm and biodiversity is increasingly being considered, in a stronger way than the increase of interest for biodiversity in literature in general. It is well established that variations in earthworm abundance can modify the community structure of other soil organisms (Bernard et al. 2012; Loranger et al. 1998), as well as plant communities (Laossi et al. 2009; Laossi et al. 2011; Eisenhauer et al. 2009; Eisenhauer and Scheu 2008; Wurst et al. 2011). Nevertheless, the co-occurrence of themes does not imply that earthworms cause an increase in biodiversity. Papers with this word association could be dealing with the diversity of earthworm communities or with any fundamental issue related to factors influencing soil biodiversity. Despite the difficult interpretation of this result, we stress the fact that this is an issue of major importance. Species diversity has been recognized as fundamental for the stability (resistance and resilience) of ecosystem services provision (McCann 2000). In artificial grasslands and models, it has been demonstrated that plant richness is generally associated with a higher redundancy between species which confers a higher reliability in the provision of ecosystem services (Tilman et al. 1996; Naeem 1998; Hector et al. 1999). The link between diversity and function in soil is less obvious. For example, a reduction in soil bacteria diversity due to the antibiotic tylosin or to mercury additions did not result in a lower multifunctionality, measured through substrate utilization profiles; nevertheless, the community response to an addition of substrate was affected in stressed as compared with control treatment (Muller et al. 2002). In the same way, Griffiths et al. (2002) found no direct relationship between bacterial, protozoan and nematode diversity and soil function, but did find an effect of diversity in response to new perturbations (Griffiths et al. 2000). So, soil function is affected by a decrease in biodiversity in the long term. As the role of earthworms is strongly associated with their impact on microbial communities, molecular and isotopic techniques will increasingly be used to shed light on how earthworms modify microbial community structure and function through the coupling of DNA, RNA, PLFA-Stable Isotope Probing with new generation sequencing methods (Stromberger et al. 2012; Bernard et al. 2012; Monard et al. 2011). Moreover, well designed laboratory and field experiments coupling basic biological and soil science measurements still have much to offer in terms of filling our knowledge gaps.

Earthworms and ecological engineering

Scientific fields of publications associating Earthworms* and another theme were very diverse. No theme appeared only in one ‘subject category’ of the Web of Science. With the exception of Soil Structure* papers, 58% of which were associated with Soil Science, the papers of no other theme was fell into a given subject category for more than 50% (Fig. 3). Ten subject categories were concerned with papers associating Earthworm* and another theme, which demonstrates the multidisciplinarity of research on Earthworms* and services.

We did not observe a significant increase in the association between the themes Earthworm* and Ecological engineering* (Fig. 1). This absence of increase has to be related to the presence of an increase in the association between Earthworms* and ecosystem services. It reflects that there is no well identified discipline that plays the role of an umbrella discipline for earthworm use (and more generally organism use) in environmental management. Concretely, the knowledge acquired on earthworm use in managing one specific ecosystem service would be difficultly transposed to another service, because of the balkanization of knowledge about organism manipulation for the management of ecosystem services. The atomization of knowledge among academic disciplines has already been pointed out as one major impediment in conservation efforts (Margles et al. 2010; Jones 2012). By the recognition of such an umbrella discipline, researchers and practitioners involved in environmental management through the use of organisms will be more susceptible to exchanges of knowledge with each other. This could save time and effort in transposing results obtained for one specific ecosystem service to another one, and to progress in taking into account ecosystem services interdependence and ecosystem multifunctionality.

A reason for the lack of such an umbrella discipline could be that ecological engineering is a young discipline, defined in 1962 by H.T. Odum, maybe still in its infancy. In parallel, the idea to use earthworms has emerged from different business sectors, based on different techniques developed from different conceptual backgrounds. Earthworm invasions are studied in conservation biology with molecular techniques such as population genetics, earthworm inoculations in the field are mainly set up by soil scientists, ecologists or agronomists for their impact on ecosystem function, and vermicompost production *ex situ* (e.g. in industrial context) is mainly a question developed in waste management. All these actors from different sectors have to gather their knowledge with the aim to propose a panel of options for ecosystem services management based on earthworm use. Other impediments could be responsible for the absence of a collective approach: from a practical viewpoint, a long time can be necessary for an inoculated population to settle, which is linked with the spatial structure of the plot, and management practices which could impede earthworm spread (Nuutinen et al. 2011). Another question arises when non native species are introduced to fill empty ecological niches, as it has been the case in Australia with European earthworms (Baker et al. 2006; Baker 2004): relationships between introduced earthworms and the endemic earthworm community are neglected, whereas these interactions can lead to drastic changes in fauna, but also microbial and plant communities.

To accelerate exchanges between scientists and engineers, we should help ecological engineering and earthworm management practices to grow, by developing scientific institutions or think tanks focused on ecological engineering and the use of organisms such as earthworms, fostering studies that take into account both academics and non-academic outputs, organizing conferences that connect people form applied and more fundamental ecological fields, editing specialized journals, launching calls for proposals that explicitly target the ecological engineering community (Barot et al. 2012). Other challenges go beyond meeting basic and applied ecology. It requires other skills than those developed in academic disciplines. Jones (2012) considers that there are three main challenges to push forward ecological engineering, including the intellectual and relational challenges. He argues that ecological engineering requires collaboration between ecologists, sociologists, economists, but also managers, policy makers, educators… If all these people are to converge, a kind of intellectual fusion is required, in which each discipline or approach should bring some 'bricks' of knowledge, such as concepts (Jones 2012). We also think that the emergence of ecological engineering is not a problem of transfer from basic to applied science (Gosselin 2011). An unified conceptual framework is actually lacking. This conceptual framework has to be pragmatic in essence, and help to identify the situations where earthworm management is relevant, choose a relevant technical approach, choose earthworm species according to the adequacy between their traits and management objectives, maintain them at the desired population size in the long term in the specific context and predict their effect and associated risks in the long term.

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Table title and note

Table 1. List of keywords used in the different searches in the Web of Science.

To avoid citing the whole list of keywords, we attributed an overall keyword marked with an "*" to each list, and call it a theme. "Earthworm*" theme is the list of different names given to these organisms, "Ecological Engineering*" theme is a list of hypothetical umbrella disciplines for ecosystem services management, the five following themes qualify specific ecosystem service by several ecosystem functions or processes related to this service and the "Diversity*" theme aims at studying the impact of ecosystem engineer such as earthworms on biodiversity per se as well as earthworm effects on ecosystem services via their interactions with other species.

Theme	List of keywords in this theme
Earthworm*	earthworms OR annelid OR oligocheta OR vermicompost
Ecological Engineering*	ecological engineering OR ecosystem services OR ecosystem goods OR biostimulation OR biological improvement OR inoculation OR restoration OR bioinoculation
Carbon Sequestration*	carbon sequestration OR carbon storage OR humic substances OR humus formation OR recalcitrant carbon OR lixiviation OR sedimentation OR carbon sink OR fossilization
Pollution Remediation*	pollution remediation OR heavy metals OR hydrocarbon OR polycyclic aromatic hydrocarbon OR persistent organic pollutant OR pesticides OR sewage sludge OR organic detritus OR radioelements OR metal remediation OR greenhouse gases OR volatile organic compounds OR
Nutrient Cycling*	nutrient cycling OR lixiviation OR leaching OR runoff OR volatization OR denitrification OR nitrogen fixation OR phosphorus fixation OR potassium fixation OR organic matter OR consumption OR degradation OR mineralization OR turn-over OR cycle
Primary Production*	Primary production OR plant growth OR plant production OR grain yield OR plant biomass OR aboveground biomass OR belowground biomass OR seed dormancy OR seed germination
Soil Structure*	soil structure OR aggregation OR aggregates OR erosion OR texture OR infiltration OR runoff OR slope OR compaction OR porosity
Diversity*	diversity OR richness OR abundance OR species number OR fauna diversity OR plant diversity OR fungi diversity OR fungus diversity OR bacteria OR archea diversity OR mammals diversity OR birds diversity OR

Table 2. Number of publications retrieved in searches in the Web of Science either for themes alone or for themes associated with the theme Earthworms*. Note that one single publication can be taken into account several times in this table if it deals with several ecosystem services.

Themes		Number of publications	
		Theme alone	Associated with Earthworms*
Earthworm* (EW)		5932	x
Ecological Engineering* (EE)		127737	178
Diversity* (DV)		636486	1223
Ecosystem services	Carbon Sequestration* (CS)	81215	132
	Pollution Remediation* (PR)	186615	650
	Nutrient Cycling* (NC)	1143959	1343
	Primary Production* (PP)	220077	590
	Soil Structure* (SS)	553709	748
Total		2955730	4864

Fig. 1 Evolution of the paradigmatic proximity between Earthworms* and different other themes year after year. On the y axis, the similarity index $(n_i \cap n_j)/(n_i * n_j)$, with i the theme "Earthworms*", and j the theme indicated along the y axis of the graphic, is a ratio taken as an indicator of the paradigmatic proximity between two themes. The absolute number of publications for each theme and theme association for the whole 1900-2009 period are given in Table 2. Slopes, their p-values and the correlation coefficient r^2 were calculated in a linear regression using the linear model.

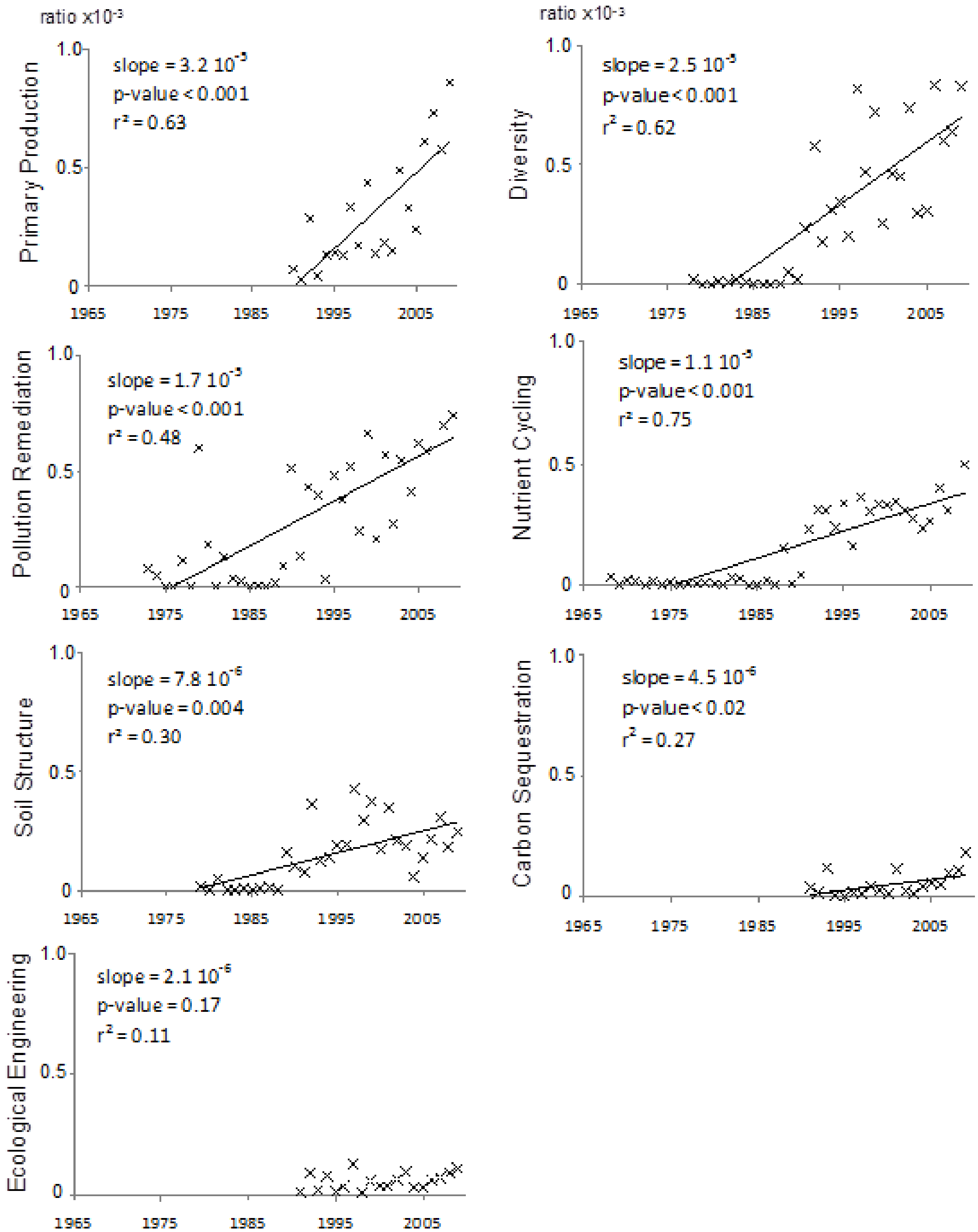
ratio x10-3
Primary Production
slope = 3.2 10-5
p-value < 0.001
r² = 0.63
Diversity
slope = 2.5 10-5
p-value < 0.001
r² = 0.62
Pollution Remediation
slope = 1.7 10-5
p-value < 0.001
r² = 0.48
Nutrient Cycling
slope = 1.1 10-5
p-value < 0.001
r² = 0.75
Soil Structure
slope = 7.8 10-6
p-value = 0.004
r² = 0.30
Carbon Sequestration
slope = 4.5 10-6
p-value < 0.02
r² = 0.27
Ecological Engineering
slope = 2.1 10-6
p-value = 0.17
r² = 0.11
1.0
0.5
0
1965
1975
1985
1995
2005

Fig. 2 Geographical origin of institutional affiliations of authors of the publications associating from one hand Earthworms* and from the other hand Ecological Engineering* (n = 178), Diversity* (n = 1223) or different ecosystem services (n = 3463, details in Table 2). A paper is attributed for one count to a country/territory if the paper carries at least one address from that country/territory. To avoid a high number of very small categories, the figure reports only the percentage for the countries with more than 4% of the total number of publications. The sum of the contributions of countries with less than 4% are: Ecological Engineering* : 15%, Carbon Sequestration* : 40%, Pollution Remediation* : 44%, Diversity* : 53%, Nutrient Cycling* : 45%, Primary Production* : 53%, Soil Structure : 42%.

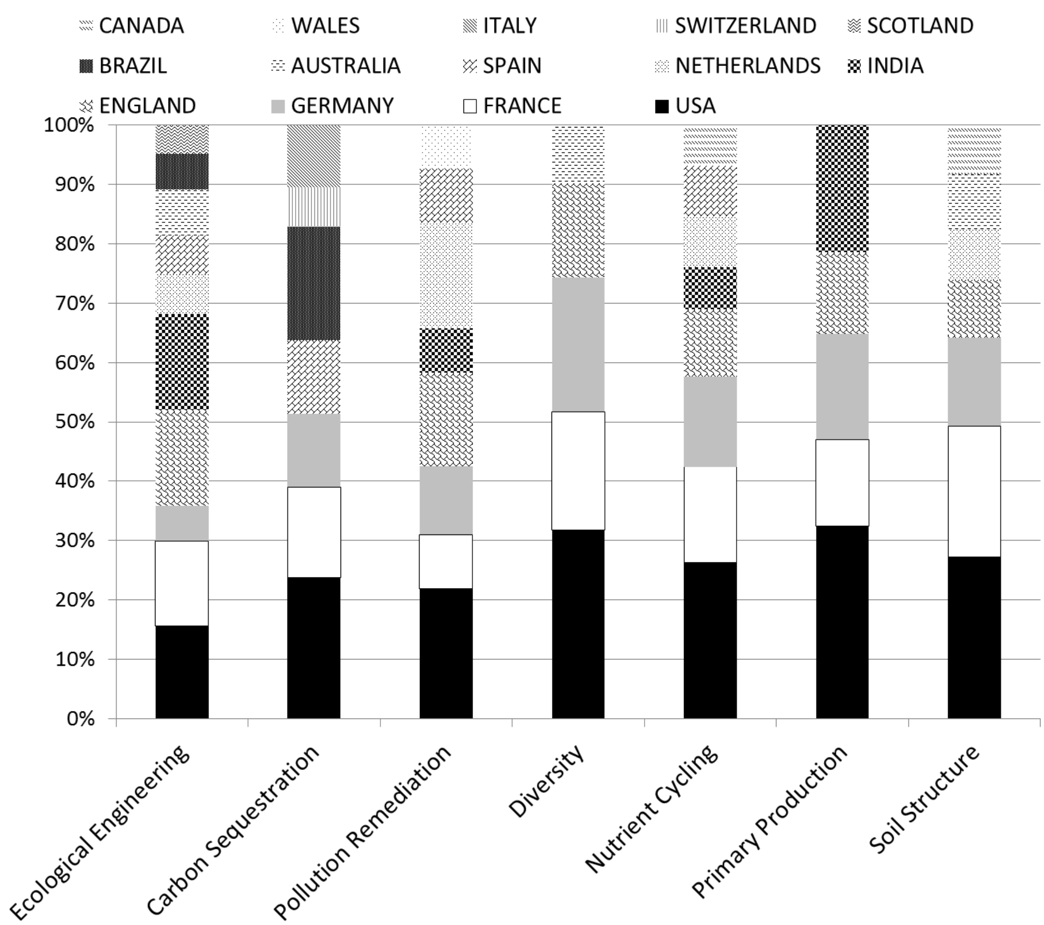

Fig. 3 Scientific fields in which publications associating from one hand Earthworms* and from the other hand Ecological Engineering* (n = 178), Diversity* (n = 1223) or different ecosystem services (n = 3463, details in Table 2) are classified in the Web of Science. The figure reports only the percentage for the countries with more than 4% of the total number of publications. The sum of the contributions of ‘Subject categories’ of the Web of Science with less than 4% are: Ecological Engineering* : 25%, Carbon Sequestration* : 42%, Pollution Remediation* : 29%, Diversity* : 39%, Nutrient Cycling* : 42%, Primary Production* : 41%, Soil Structure : 29%.